Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **33**, 1839–1850 (2008)
Published online in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/esp.1738

Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas

Daniel E. Buschiazzo[1,2,3]* and Ted M. Zobeck[4]

[1] *INTA Anguil, Argentina, cc 11, 6326 Anguil, Argentina*
[2] *Facultad de Agronomía, UNLPam, Argentina, cc 300, 6300 Argentina*
[3] *CONICET, Argentina*
[4] *USDA-ARS, Lubbock, Texas*

Correspondence to: Daniel E. Buschiazzo, INTA Anguil, Argentina, cc 11, 6326 Anguil, Argentina. E-mail: buschiazzo@agro.unlpam.edu.ar

Abstract

Wind erosion is an important soil degradation process in the semi-arid Pampas of Argentina, but no attempts have been made to predict the process in this region. One limitation for the use of event-based wind erosion prediction models is the lack of reliable climatic data to initiate these models. As an effort to apply wind erosion models, we compared field wind erosion measurements carried out during 4 years in a bare soil reference plot (RP) and during 3 years in the same soil with different tillage conditions: conventional (CT) and no-till (NT). Wind erosion was predicted with: (1) subroutines for single storm event versions of the wind erosion prediction system (WEPS) and the revised wind erosion equation (RWEQ), for which the climatic data of each single storm were used, and (2) the wind erosion equation (WEQ) for full rotation periods, for which long-term climatic records (1961–2004) were used. Wind erosion field measurements were carried out with BSNE samplers in 1-ha plots. Regression of predicted soil erosion rates from WEPS ($y = 0{\cdot}5192x + 0{\cdot}0589$, $R^2 = 0{\cdot}89$) and RWEQ ($y = 0{\cdot}5691x - 7{\cdot}071$, $R^2 = 0{\cdot}90$) predictions with field measurements of soil erosion rates obtained in RP (54·51 kg m^{-1} on average) were highly significant, but both models underestimated wind erosion by 40–45 per cent. Predictions of wind erosion made with RWEQ were highly sensitive to variations in the soil crusting factor (SCF), varying from 60·5 t m^{-1} when predictions for a single storm were made using the SCF default data to 0·699 t m^{-1} when SCF was deduced from visual field observations. The WEQ predictions agreed adequately with measured erosion for 16 rotation periods either when using a climatic *C* factor value of 92, corresponding to the 1961–2004 period ($y = 0{\cdot}9422x - 1{\cdot}9248$, $R^2 = 0{\cdot}96$) or a *C* factor value of 80, corresponding to the moister 1985–2004 period ($y = 0{\cdot}7612x - 1{\cdot}5543$, $R^2 = 0{\cdot}96$). Neither WEPS nor RWEQ predicted the low amounts measured in CT and NT (3·86 kg m^{-1} on average) for storms lasting approximately 24 hours. High plant or residue soil coverage as well as high oriented surface roughness eliminated erosion according to WEPS and RWEQ. These results indicated that WEQ can be used as a reliable prediction model for long-term predictions of wind erosion in the semi-arid Pampas, even when run with limited available climatic data for this region. Copyright © 2008 John Wiley & Sons, Ltd.

Keywords: **erosion prediction models; wind erosion; semiarid regions**

Received 31 January 2007; Revised 31 October 2007; Accepted 31 October 2007

Introduction

The semi-arid Pampa of Argentina is one of the regions of the world where wind erosion has been identified as an important soil degradation process (Dregne, 1986). Although important, little is known about the characteristics of the wind erosion processes in this region and no prediction models used to develop wind erosion mitigation strategies have been tested. This issue is particularly important for soils of this region where agriculture is carried out with conventional tillage systems. Such systems leave the soil bare and in a highly erodible condition during most of the year.

Maps of soil susceptibility to wind erosion were made for north Argentina (Torres and Fernández, 2000) and the central semi-arid Pampas (Michelena and Irurtia, 1995; Covas and Glave, 1996). Studies by Buschiazzo and Taylor (1993) showed that Haplustolls transformed into Ustochrepts after wind erosion, and Aimar (2002) demonstrated that wind erosion was lower in an Entic Haplustoll than in a Typic Ustipsamment. No attempts were made to develop a model to predict the process in this region specifically for agricultural soils.

The most common models used to predict wind erosion at the field scale are the wind erosion equation (WEQ, Woodroff and Siddoway, 1965), the revised wind erosion equation (RWEQ, Fryrear *et al.*, 1998) and the wind erosion prediction system (WEPS, Hagen, 1991). The WEQ predicts wind erosion for total rotation periods but not for short periods of time. This does not allow users to identify critical periods within a rotation where wind erosion may be higher than recommended. The RWEQ and WEPS make both annual and period estimates, allowing the user to change management practices within a rotation period or even within a crop growth period and for single erosion events.

Some attempts have been made to calibrate these models in the USA. Fryrear *et al.* (1998) found that correlations between observed and RWEQ-estimated field soil loss was 0·97 in 11 wind erosion events. Zobeck *et al.* (2001) found that RWEQ underestimated wind erosion for 41 erosion events measured at six locations in the USA. Similar results were found for 24 wind erosion events that occurred in Big Spring, Texas (Van Pelt *et al.*, 2004). A lack of information exists on the usefulness of these models for predicting wind erosion under conditions different from those in the USA, including semi-arid Argentina.

One basic need of these models is a long-term climatic database. The database uses wind speed and wind direction data, but each model uses these data and other climatic variables in different ways.

The climatic database of WEQ is based on monthly averages of wind speed and wind direction, which are used to determine wind energy and wind preponderance. Such data are complemented in the model with the *C* value, an index of the climatic conditions of a determined zone, which is a function of precipitation and temperature.

The RWEQ and WEPS climatic databases are based on wind speeds and wind direction sampled once each hour or 3 hours, along with other climatic variables, such as solar radiation, temperature and precipitation. These values are processed in the climatic subroutines as statistical variables of monthly averages. Five years is the minimum dataset of climatic data needed to develop climatic subroutines of RWEQ and WEPS. Wind speed and direction data are used to calculate Weibull shape (k) and scale (c) parameters. Available climatic databases of Argentina are scarce and not accurate enough to achieve RWEQ and WEPS requirements. The national database of INTA (Instituto Nacional de Tecnologia Agropecuaria) includes many years of measurements (mostly since 1961) but they are based on daily averages of wind speed and direction. This kind of climatic information fits requirements of WEQ better than RWEQ and WEPS.

The RWEQ and WEPS allow the prediction of erosion with measured data. This can be done by specifying climatic, soil and plant cover conditions existing during a storm in a 'stand-alone' submodel of WEPS and in the case of RWEQ by processing its equations in Excel. Since climate may change through time, historic changes in climate may need to be considered when specifying dates used for climate database compilation. For example, somewhat recent changes in climate appear to have occurred in the study area. Since 1985, a substantial increase in annual precipitation of almost 200 mm per year has occurred in this region but no changes in wind characteristics have been reported (Casagrande and Vergara, 1996). Higher amounts of rainfall and similar wind characteristics of the last 19 years decreased the climatic C factor of WEQ, which is a direct function of wind speed cubed and inverse function of the quotient precipitation/potential-evapotranspiration (Woodruff and Siddoway, 1965). Therefore, wind erosion predicted with WEQ should be higher when using climatic records of the period 1961 to 2004 than when using the last 19 years of climatic data alone.

The objectives of this study were to test the applicability of WEPS, RWEQ and WEQ to predict wind erosion for Argentinean conditions. We tested the sensitivity of WEQ to make predictions of wind erosion for Argentinean conditions using two different climatic conditions. In addition we compared the erosion estimate made using the 'stand-alone' model of WEPS and the single event version of RWEQ with single-event field data for different farm management practices.

Materials and Methods

Wind erosion was measured in three 1×1 ha field plots located in an 8-year rotation experiment (Modulo de Labranzas) located in the Facultad de Agronomia of the Universidad Nacional de La Pampa, Santa Rosa, Argentina (36°30′ S and 64°30′ W; Figure 1). One of the 1×1 ha fields remained bare and with minimum soil surface roughness during wind erosion measurements (reference plot, RP), while the other two plots were subjected to a unique rotation system and two different tillage intensities: no till (NT) and conventional tillage (CT). Details of the crop rotations and tillage

DOI: 10.1002/esp

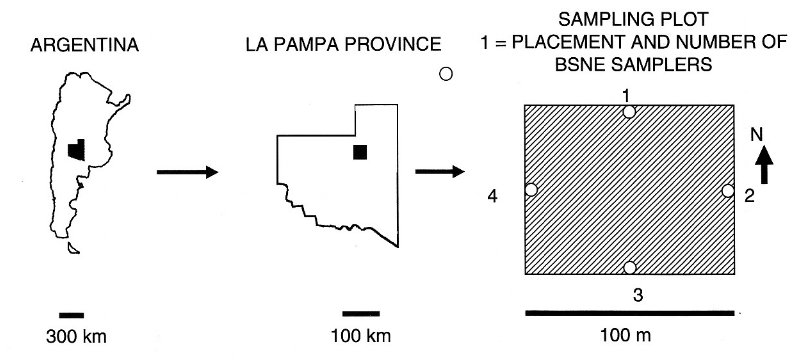


Figure 1. Placement and identity number of BSNE samplers. The distribution of BSNE samplers is the same for RP, CT and NT plots.

operations are given in Table I. The surrounding fields of the measuring plots remained 100 per cent covered with vegetation or plant residues during wind erosion measurements. Some of the species covering the soil were *Avena fatua*, *Avena sativa* and *Chenopodium album*.

Mean annual temperature of the region is 16 °C and mean annual rainfall is 550 mm. Mean annual wind speed of this region varies between 10 and 15 km h^{-1}, and prevailing wind direction is from the north and the southwest (Casagrande and Vergara, 1996). The highest wind speeds occur between late winter (August and October) and spring months and average 20–25 km h^{-1}, with frequent gustiness of 50–60 km h^{-1}.

The soil of the experimental site was a fine sandy loam Entic Haplustoll with an A–AC–C_1–C_{2k} horizon sequence. The organic matter content (Walkley and Black, 1934) of the A horizon was 1·75 per cent in NT, 1·43 per cent in CT and 1·25 per cent in RP. The granulometric composition, determined with the pipette method was 12·2 per cent clay and 19·7 per cent silt in CT and NT and 10·2 per cent clay and 17·2 per cent silt in RP.

Wind eroded material was collected in all sampling plots (RP, NT and CT) by means of BSNE aeolian sediment samplers (Zobeck, 2002), which were placed at three different heights (0·135, 0·50 and 1·50 m) in four locations, corresponding to the middle point of each side edge of each plot (Figure 1). The BSNE samplers have a 95 per cent sampling efficiency to catch sandy material transported by wind (Fryrear, 1986).

Wind erosion measurements were carried out in years 1995, 2001, 2002 and 2003 in RP, and in 2001, 2002, and 2003 in NT and CT. Twenty wind erosion storms were measured during year 1995 based on results of Aimar (2002). Nine storm events were measured in 2001, 55 in 2002 and 25 in 2003. Wind erosion in NT and CT was measured during the fallow and the growth of summer crops (July to March).

The horizontal flux, M, at each sampling point was calculated by integrating the equation (Stout and Zobeck, 1996):

$$M = f_o(1 + Z/\sigma)^{-\beta} \tag{1}$$

where M is the horizontal mass flux expressed in kg m^{-1}, f_o is the movement of the soil at the soil surface, σ is the height at which 50 per cent of the material is carried by saltation, and β is a regression coefficient.

This equation allowed the integration of the eroded material as a function of height between 0 and 1·5 m in order to calculate the horizontal flux at each sampling point. The amount of eroded material within the plots was calculated subtracting the amount of airborne sediment entering the plot from that leaving it in the direction of prevailing winds. According to Figure 1, when the winds blew from the N, the eroded material was calculated as the difference between the material passing by sampling point 3 minus the material passing by sampling point 1. When the winds blew from NE, the eroded material was calculated as the difference between the averaged amount of material passing by points 3 and 4 minus the averaged amount of material passing by points 1 and 2.

The prevailing direction of the wind in each storm was determined using a SENSIT (Zobeck, 2002), a device that electronically measures the impact of saltating particles and allows the determination of the period of time within each storm when wind erosion occurred.

Digital pictures of NT and CT were taken every 20 days to determine the percentage of surface plant residue and canopy cover. Pictures taken perpendicular to the soil surface from a 1·50 m height were used for residue cover determination and, pictures taken parallel to the soil surface from a 0·50 m height were used for canopy cover determinations. A simulated line-transect method was used on the PC screen to determine residue cover and percentage of plant cover.

DOI: 10.1002/esp

Table I. Main characteristics of soil management conditions

Year	Month	RP (reference plot) Crops and tillage operations	Residues (flat or standing) or weed cover (%)	Canopy height (cm)	NT (no tillage) Crops and tillage operations	Residues (flat or standing) or weed cover (%)	Canopy height (cm)	CT (Conventional tillage) Crops and tillage operations	Residues (flat or standing) or weed cover (%)	Canopy height (cm)
1995	12 months	Disker.[a]	0	0	na	na	na	na	na	na
2001	January		0	0	Start rotation	75	80	Start rotation	12	82
					sunflower growth			Sunflower growth		
	March		0	0	sunflower harvest	68	85	Sunflower harvest	5	87
	April	Disker	0	0		66	0		25	
	September		0	0	herbicide appl.	58	0	Disker	0	0
	November		0	0	sunflower planting	55	0	Sunflower planting	5	0
2002	January	Disker	0	0		50	25		10	33
	March		0	0	Sunflower harvest	98	90	Sunflower harvest	10	100
	August		0	0	Herbicide appl.	95	0	Disker	0	0
	October					93	0	Disker	0	0
	November		0	0	Soybean planting	90	0	Soybean planting	10	0
2003	January		0	0		69	20		12	30
	April	Disker	0	0	Soybean harvest	58	35	Soybean harvest	10	40
	August		0	0	Herbicide appl.	72	0	Disker	0	0
	September	Disker	0	0	Herbicide appl.	65	0		15	0
	November		0	0	sunflower planting	60	0	Sunflower planting	0	0
	December	End rotation	0	0	End Rotation	50	20	End Rotation	0	28

[a] In January, March and September.
na = not analysed

Random roughness of all plots was measured using the chain method (Saleh, 1993) and the oriented roughness was measured using the ridge height and space method of Zingg and Woodruff (1951). Roughness was measured in all cases after each rain event or after each tillage operation.

An automated meteorological station was placed in the centre of the reference plot during measurements made between 2001 and 2003. One minute means of wind speed at 2 m height, and wind direction, radiation, precipitation and SENSIT pulses were obtained with this station. In a few cases, when the meteorological station was downloaded with a frequency greater than a week, and in order to avoid exceeding the data logger memory capacity, all mentioned parameters were averages of 12 minutes elapsed time. The SENSIT is an electronic device that allows the estimation of erosion events duration by measuring the impacts of saltating particles at a frequency of 1 Hz (Zobeck, 2002). In this study, the SENSIT also was used to obtain the prevailing wind direction of each storm, estimated as the average wind direction during periods in which this device detected saltation.

Climatic data of 1995 were obtained from an automated meteorological station located 1 km away from RP, which gave hourly averages of wind speed, wind direction, radiation, precipitation and air temperature.

The stand-alone subroutine of WEPS (USDA, 1996) and an Excel worksheet version of RWEQ were used to predict wind erosion for single events for the RP. The soil characteristics used for both models are listed in Table II. Most of considered variables remained constant during the experiment, except for soil crust thickness, soil crust fraction and soil surface roughness (Allmaras random roughness), which were affected by precipitation and tillage practices.

Characteristics of the 28 storms used for the single event subroutines of WEPS and RWEQ are listed in Table III. These storms correspond to dates when climatic data with 1 min or 12 min resolution were available.

The WEQ predictions for the reference plot were made for the period 1995–2003. The estimated erosion in each year was obtained by dividing the total amount by 9 (number of years of the rotation). We used the predicted erosion

Table II. Soil properties of reference plot used in RWEQ and WEPS for single events predictions

Soil condition	Units	Value
Number of layers		1
Layer thickness	cm	230
Sand (>0·02 mm)	Mg Mg^{-1}	0·726
Silt (0·002–0·02 mm)		0·172
Clay (<0·002 mm)		0·102
Sand fraction – fine (0·02–0·2 mm)	kg kg^{-1}	0·6
Rock fragments	m^3 m^{-3}	0
Bulk density	Mg m^{-3}	1·25
AGMD	mm	1·75
AGSD		15·1
Maximum aggregate size		25
Minimum aggregate size		0.01
Aggregate density	Mg m^{-3}	1·83
Aggregate stability	ln(J kg)	1·874
Soil crust thickness	mm	0–5
Soil crust density	Mg m^{-3}	1·2
Soil crust stability	ln(J kg)	1·87
Soil crust fraction	m^2 m^{-2}	0–1
Loose material on crust-mass	kg m^{-2}	0
Loose material on crust-fraction	m^2 m^{-2}	0
Allmaras random roughness	mm	2–6
Roughness orientation	degree	0
Roughness height	mm	0
Roughness spacing		0
Roughness width		0
Initial water content		
Saturation water content	kg kg^{-1}	
Wilting point water content		

AGMD: Aggregate geometric mean diameter; AGSD: Aggregate geometric standard deviation.

DOI: 10.1002/esp

Table III. Main characteristics of storms used for wind erosion predictions for single events made with WEPS and RWEQ, and erosion measured in a bare and non-roughed soil (RP), in a no-till (NT) plot and a conventional tilled soil (CT) plot. Field wind erosion measurements were made with three BSNE samplers (0·135, 0·50 and 1·50 m height)

Date	Storm duration (hh:mm)	Wind direction	Mean wind speed (m s^{-1})	Standard deviation	Measured erosion (kg m^{-1})		
					RP	NT	CT
1-Nov-02	19:30	N	5·07	2·50	2·70	0·00	0·00
6-Nov-02	7:00	N	12·35	2·33	699·00	1·24	2·13
7-Nov-02	17:36	N	7·86	4·03	300·00	5·26	3·32
14-Nov-02	24:00	NE	2·32	2·58	9·75	0·00	0·00
30-Nov-02	16:24	NE	0·00	0·00	5·67	0·00	0·00
7-Dec-02	19:36	N	2·84	2·32	0·21	0·00	0·00
17-Dec-02	20:00	N	3·54	1·70	75·25	0·00	0·00
18-Dec-02	25:00	NE	5·95	1·43	640·00	3·61	6·23
20-Dec-02	23:00	N	3·31	1·90	17·37	2·43	3·25
26-Dec-02	25:00	N	3·37	2·75	61·69	10·21	7·40
10-Jan-03	20:30	N	2·86	1·26	25·40	0·00	0·00
21-Jan-03	24:00	N	2·34	2·35	33·71	0·00	0·00
25-Jan-03	22:00	NW	4·75	2·40	29·55	3·90	3·50
27-Jan-03	25:00	SE	2·79	2·65	8·87	5·23	4·80
29-Jan-03	25:15	W	3·92	2·57	38·16	2·35	2·93
31-Jan-03	23:24	SW	2·70	2·17	20·65	0·00	0·00
5-Feb-03	24:15	N	3·45	2·67	28·00	0·00	0·00
7-Feb-03	25:00	N	3·62	2·83	40·40	8·00	7·90
12-Feb-03	23:00	W	2·09	2·20	6·34	0·00	0·00
14-Feb-03	22:48	NW	2·33	3·19	460·64	11·00	15·67
19-Feb-03	48:00	N	4·01	3·19	152·16	5·25	19·50
24-Feb-03	45:12	SW	5·26	2·56	60·53	4·56	9·37
26-Feb-03	48:24	N	4·67	1·76	28·29	0·00	0·00
28-Feb-03	23:24	N	3·63	3·11	131·52	3·50	5·25
17-Mar-03	23:50	N	2·44	0·82	7·34	0·00	0·00
25-Mar-03	24:15	NE	4·65	2·54	106·27	4·00	7·00

of years 1995 and 2001–2003 to compare with field data (Table III). The WEQ predictions for CT and NT were made for rotations developed during 2001, 2002 and 2003. The individual predictions of WEQ for each half rotation period within each year (summer and winter crops) were compared with measured erosion data.

The 1961–2004 INTA climatic data records for Santa Rosa, containing wind speed at 2 m height, wind direction, precipitation, radiation and potential evapotranspiration were used to calculate the climatic factor C (Skidmore, 1986), according to the following equation:

$$C = 34{\cdot}483\ [v^3/(PE)^2] \tag{2}$$

where v is the cumulative sum of the mean monthly wind velocity for a year for a particular geographical location, and PE is the Thornthwaite P–E ratio, $10(P/E)$; where P is the cumulative sum of the mean monthly precipitation and E the cumulative sum of the mean monthly potential evapotranspiration. We calculated C for the period 1961–2004 and for the moister period 1985–2004.

Wind energy and prevailing wind direction required by WEQ were calculated according to Skidmore (1965), calculating the wind erosion force vector ($\boldsymbol{r}_j$) by summing for all speed groups with wind speeds greater than 8 m s^{-1}, the product of mean wind speed cubed and a duration factor for a specific direction as expressed by Equation (2)

$$\boldsymbol{r}_j = \sum_{i\text{th}=1}^{n} u_1^3 f_1 \tag{2}$$

where u_1^3 is the wind speed within the ith period group, f_i is a duration factor which is expressed as the percentage of the total observations that occur in the ith direction within the ith wind speed group. The subscript j values indicate

DOI: 10.1002/esp

Table IV. Example of a climatic datasheet for Santa Rosa for the 1961–2004 period. In this case January 1995

Day of month	Wind speed at 2 m height (m s⁻¹)		Wind direction	Solar radiation (MJ m⁻²)	Precipitation (mm)	PET Penman[a] (mm)
	Day	Night				
1	6·7	5·7	N	400	0	3·5
2	8·0	11·4	Variable	385	0	3·1
3	4·7	1·4	Variable	190	0	1·1
4	8·2	8·9	SE	200	0	1·2
5	8·3	6·8	SW	190	0	0·9
6	4·7	1·8	S	459	0	1·7
7	6·0	3·2	NE	349	0	2·2
8	8·2	4·4	N	410	0	2·2
9	11·1	6·9	Calm	406	0	1·8
10	7·1	0·0	SW	485	0	2·2
11	4·7	1·2	W	424	0	2·5
12	3·3	3·5	Calm	346	0	2·4
13	7·3	2·6	Variable	375	0	3·0
14	3·9	2·4	Variable	182	0	2·2
15	4·3	2·1	Variable	444	0	2·7
16	5·7	4·3	Calm	137	0	2·3
17	10·2	2·8	SW	292	0	3·0
18	4·6	1·5	S	447	0	1·6
19	11·7	10·3	Variable	322	0	3·2
20	6·2	1·9	Variable	492	0	2·0
21	6·7	0·7	W	509	0	2·4
22	6·9	7·9	Variable	500	0	1·8
23	8·0	6·9	NE	188	0	2·0
24	10·0	7·9	NE	383	0	2·4
25	4·7	4·1	Variable	471	0	1·6
26	10·0	12·6	Variable	432	0	1·0
27	5·7	1·0	SW	463	0	1·8
28	4·0	2·2	NE	297	0	1·9
29	8·0	4·8	NE	404	0	1·7
30	2·5	1·2	Calm	484	0	1·2

[a]Potential evapotranspiration calculated with Penman.

direction and take on values from 0 to 15, representing the 16 principal compass directions. An example of a climatic datasheet used for the climatic database of WEQ is shown in Table IV.

Comparison between calculated and measured data was done by means of simple linear regression analysis in every case.

Results and Discussion

Tests of WEPS and RWEQ for single events with the data of RP correlated well with 28 measured dust events (mostly obtained from 24-h measurements) in RP (Figure 2a and b). Fittings of both equations were the same but the WEPS slope (0·59) and intercept (0·0589) were slightly better than of the RWEQ (0·57 and −7·071, respectively).

Both models tended to underestimate the observed wind erosion measurements. These underestimations were approximately 45 per cent for RWEQ and 40 per cent for WEPS at measured values of 300 kg m^{-1}. These values are similar to those obtained by Zobeck *et al.* (2001) and van Pelt *et al.* (2004), who found that underestimations of RWEQ for some soils of the USA varied between 35 and 55 per cent. The origin of these underestimations is not clear. Buschiazzo and Zobeck (2005) found that the use of different equations for calculating the horizontal mass flux can produce large differences in the amount of the eroded material. These authors also mentioned that results of field measurements of wind erosion can be highly variable depending on the heights at which the dust samplers are placed above the soil surface.

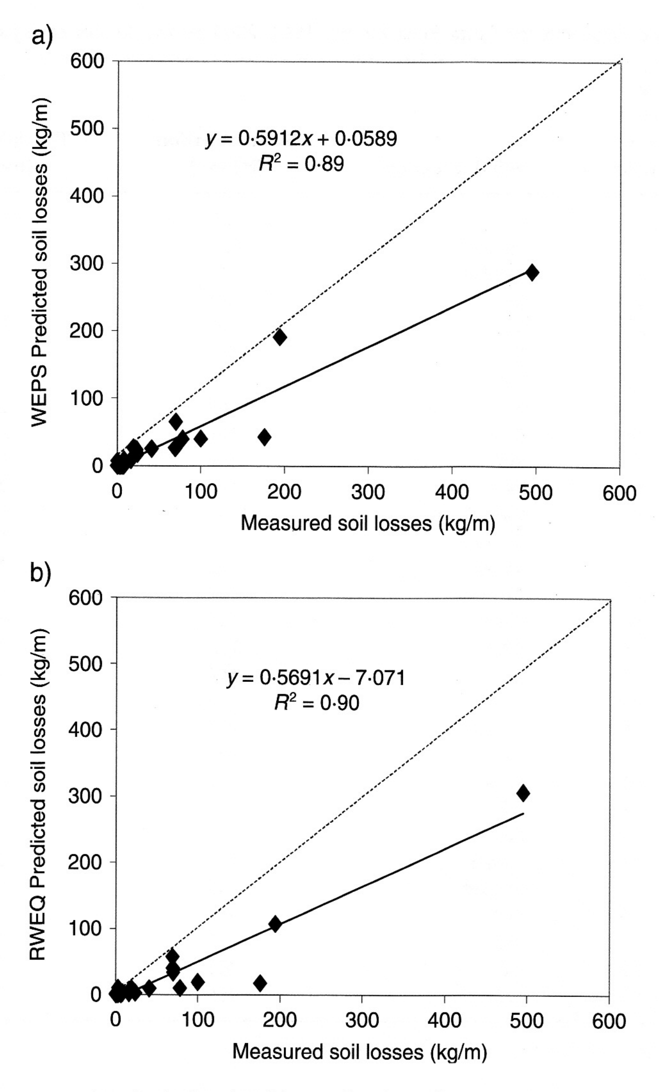


Figure 2. Relations between measured and calculated soil losses for the reference plot (RP) for single events using (a) WEPS and (b) RWEQ. Dotted lines represent 1:1 fits and solid lines represent regressions.

Predictions made with RWEQ were highly sensitive to variations in soil surface crusting in RP, represented by the soil crusting factor (SCF), which measures the susceptibility of the soil to form crust, depending mainly on its clay contents. The RWEQ default value for the SCF calculation was 0·72, based on the empirical equation used by Fryrear *et al.* (1998) that relates SCF with the clay and organic matter contents of the soil. With this SCF, RWEQ simulated 60·5 t m^{-1} (60 500 kg m^{-1}) wind erosion for the 6 November 2002 storm. A SCF of 0·20 was arbitrarily fixed on the basis of the best fit that the 6 November 2002 storm wind erosion produced on the fit of the regression between observed and predicted wind erosion (Figure 3). This value was to some extent controlled on the basis of visual observations from the digital photographs used for soil roughness and canopy measurements. A SCF of 0·20 produced an erosion rate of 306 kg m^{-1}, almost 200 times lower than the default data (Figure 3). Soil surface crusting was produced in this case by a 24·5 mm rainfall that occurred 4 days before the 2 November 2002 storm.

Soil surface crusting is critical in determining wind erosion because it can increase or decrease erosion amounts (Zobeck, 1991). No universally accepted method to measure crusting has been developed and very few models include this variable in erosion estimates (Zobeck *et al.*, 2003). The SCF largely depends on rain amounts. The full version of RWEQ includes a link between climatic conditions and SCF, which allows the prediction of crust formation and degradation with time, but the RWEQ calculation worksheet for single events does not link the climatic conditions with SCF.

DOI: 10.1002/esp

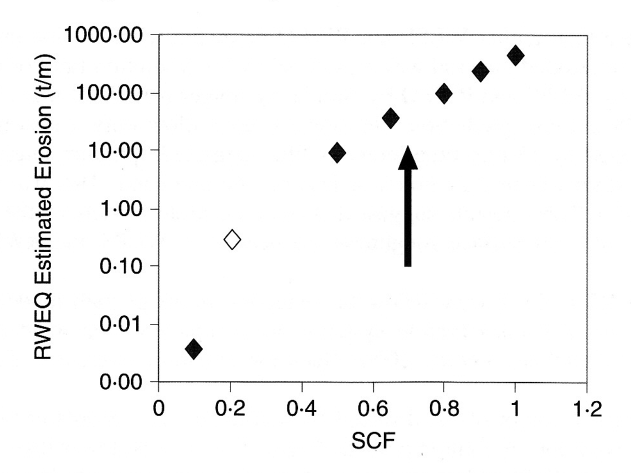


Figure 3. Erosion calculated with RWEQ as a function of the soil crusting factor (SCF). The open diamond indicates the SCF used in storm of 6 November 2002 and the arrow the SCF deduced from RWEQ default data.

Measured wind erosion for single erosion events averaged 3·86 kg m^{-1} (SD = 5·11) in CT and NT (Table III). Neither the stand-alone subroutine of WEPS nor the single event Excel worksheet of RWEQ predicted erosion in most of these cases, although some storms had wind speed means or gusts higher than 8 m s^{-1}, the minimum speed required to start erosion (Hagen, 1991). Hagen (personal communication, 2004) indicated that low amounts of erosion were excluded from WEPS to improve computation run times because no precise surface measurements were available to enable meaningful calculations. The lack of erosion predicted by both models was possibly due to the elevation of the wind profile produced by the high oriented soil roughness and soil canopy cover and/or residues. To test this effect we analysed the 6 November 2002 storm, which produced a large amount of eroded material in RP (699 kg m^{-1}) during a relatively short time period (420 min) from a constant wind direction (N–S) (Table III). Such conditions avoided measurement errors due to variations in wind direction already detected by Buschiazzo *et al.* (1999) and Zobeck and van Pelt (2006).

Although no wind erosion was predicted by either the WEPS or RWEQ models, some erosion occurred in the NT and CT plots for the 6 November 2002 storm. The lack of predicted erosion in no-till was related with the high percentage of flat residues lying on the soil surface (higher than 90 per cent, Table I and Figure 4). The lack of erosion in CT was attributed to the combined effect of high oriented soil roughness perpendicular to the prevailing wind direction (oriented soil roughness = 30 cm) and the existing canopy cover (10%).

We suspect that the calculations of the horizontal mass flux of some storms in NT and CT may have some errors, mainly in the storms occurring with high canopy development. In most of these cases, very low amounts of material were captured by the lower BSNE samplers as a consequence of high canopy cover, which elevated the threshold velocity. This caused a poor fit of the observed horizontal flux data with Equation (1). In these cases, Equation (1) may not be the best equation to describe the sediment distribution with height. Detailed consideration of this question is beyond the scope of this article and needs to be studied further.

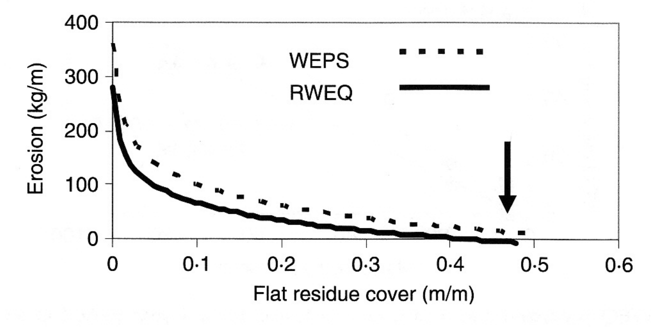


Figure 4. Erosion predicted with WEPS and RWEQ as a function of soil cover with flat residues for the 2 November 2002 storm conditions. Arrow indicates the minimum amount of residues existing in no-till conditions during all measured storms.

DOI: 10.1002/esp

Model simulations indicated that neither WEPS nor RWEQ predicted wind erosion on a daily basis from NT and CT plots and that the amount of eroded material was mostly below the resolution limit of both models. We did not test the erosion amount detected by WEPS and RWEQ by simulating longer periods of time. This is not possible with the stand-alone version of WEPS because predictions for single events allow only a maximum of 96 time units. As a result, if wind data are averaged by 15-min time intervals (the suggested optimum interval time to be considered in WEPS; Hagen, 1991), only storms lasting 24 hours or less can be predicted. This was the measuring period of all storms in this study (Table IV). These results suggest that more accurate models of the relationships between wind erosion and both soil cover and soil surface roughness are needed in WEPS and RWEQ for short-duration wind erosion events.

Although wind erosion in NT and CT were below the detection limits of both models, such soil losses were not expected in NT, as it is known that conservation systems can completely stop wind erosion and even can retain particles transported by wind (Buschiazzo *et al.*, 2006). Such losses can be overcome if higher plant residues can be left over the soil surface.

The WEQ predictions using a *C* factor of 92, deduced from climatic data records of the period 1961–2004, agreed adequately with measured erosion for 16 rotation periods (Figure 5a). A slope lower than 1 and a negative intercept of the regression equation produced slight underestimations at wind erosion amounts lower than 35 t ha^{-1} and overestimations above this value.

We calculated the *C* value for the period 1985–2004 in order to test if the wetter conditions that had occurred since 1985 as a consequence of significant increases in precipitation affected the predictions of WEQ. Casagrande and Vergara (1996) found that precipitation averaged 720 mm in the wet period and 550 mm in the whole dry period. The *C* factor for the wet period was 80, compared with 92 for the period 1961–2004. This change in *C* decreased the predicted erosion of WEQ by only 12 per cent (Figure 5b). This result supports the notion that relatively small changes in WEQ predictions would result if the model were used with climatic databases from wetter data compilation

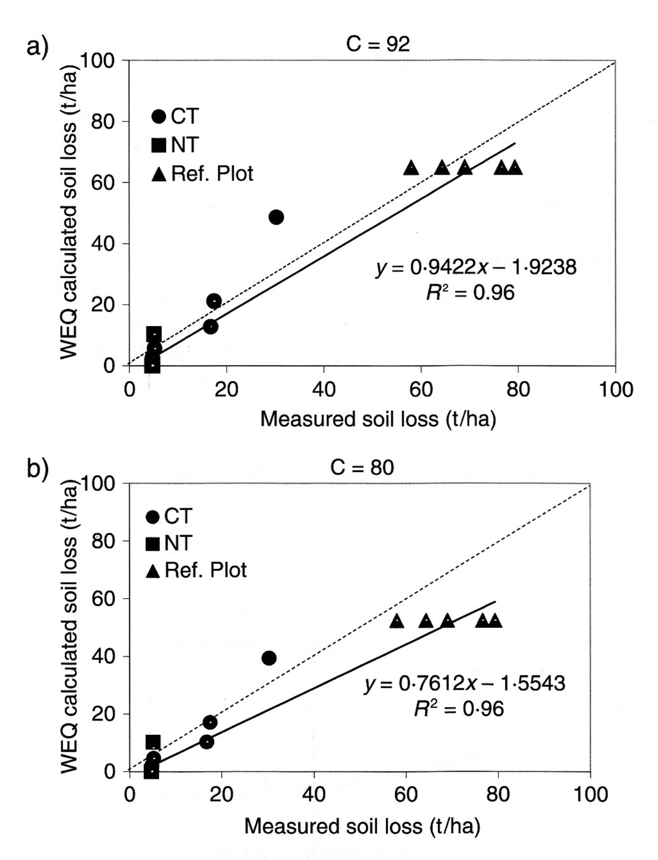


Figure 5. Relation between WEQ predicted and measured soil losses for a 1-year period in an Entic Haplustoll of Argentina under conventional tillage (●), no till (■) and in a bare soil (▲) using a climatic *C* factor of (a) 92 and (b) 80. Dotted lines represent 1:1 fits and solid lines represent regressions.

periods. The small difference in wind erosion measured during the moister 1985–2004 period with predicted wind erosion based on climatic data of the whole dryer period 1961–2004 indicates that even when rains increased in this region, wind erosion was not reduced. This probably has to do with the climatic conditions existing in semi-arid regions where rain events in the spring, when the soils are bare, are followed by dry periods during which the soil surface dries very quickly and its susceptibility to wind erosion can dramatically increase.

Conclusions

From former results we concluded that:

(1) Wind erosion predictions for single storms made with WEPS ($y = 0{\cdot}5192x + 0{\cdot}0589$, $R^2 = 0{\cdot}89$) and RWEQ ($y = 0{\cdot}5691x - 7{\cdot}071$, $R^2 = 0{\cdot}90$) fitted well with wind erosion measurements in a bare and smooth soil (54·51 kg m^{-1} on average).
(2) The RWEQ and WEPS wind erosion predictions for the bare and smooth soil were 40–45 per cent lower than field measurements.
(3) Neither WEPS nor RWEQ predicted relatively small amounts of soil erosion (3·86 kg m^{-1}) for single storms lasting approximately 24 hours when the soil is covered with plants, residues or had a high oriented surface roughness.
(4) Predictions made with RWEQ were highly sensitive to variations in the soil crusting factor (SCF), varying from 60·5 t m^{-1} (60 500 kg m^{-1}) when predictions for a single storm were made using SCF default data to 699 kg m^{-1} when SCF was fixed on the basis of visual SCF field observations.
(5) The WEQ predictions agreed adequately with measured erosion for 16 rotation periods of one year each, either when using a climatic C factor value of 92, corresponding to the 1961–2004 period ($y = 0{\cdot}9422x - 1{\cdot}9248$, $R^2 = 0{\cdot}96$) or a C factor value of 80, corresponding to the moister 1985–2004 period ($y = 0{\cdot}7612x - 1{\cdot}5543$, $R^2 = 0{\cdot}96$).
(6) The WEQ can be used as a reliable prediction model for long-term predictions of wind erosion in the semi-arid Pampas, even when run with the limited climatic data available for this region.

Aknowledgements

This study was funded by Eppley Foundation for Research, Consejo Nacional de Investigaciones Cientificas y Tecnicas (CONICET, Argentina, PIP 2107), Facultad de Agronomia, UNLPam (Proyecto Nr. 4/00), and SECYT Argentina (PICTo 08-13166). Authors wish to thank to Ed Skidmore, Lawrence Hagen, John Tatarko and Larry Wagner of WERU, USDA–ARS, Manhattan, Kansas, for providing the 'stand-alone' version of WEPS.

References

Aimar S. 2002. *Estimaciones cualitativas y cuantitativas de pérdidas por erosión eólica en suelos de la Región Semiárida Pampeana Central*. MSc. thesis. Universidad Nacional del Sur, Argentina; 143 pp.

Buschiazzo DE, Taylor V. 1993. Efectos de la erosión eólica sobre algunas propiedades de suelos de la región Semiárida Pampeana Argentina. *Ciencia del Suelo* **10**: 46–53.

Buschiazzo DE, Zobeck TM. 2005. Airborne horizontal mass flux calculated with different equations. *2005 Annual ASAE Annual International Meeting*, Tampa, Florida, 17–20 July.

Buschiazzo D, Zobeck TM, Aimar SB. 1999. Wind erosion in loess soils of the semiarid Argentinian Pampas. *Soil Science* **164**: 133–138.

Buschiazzo DE, Abascal S, Zobeck T. 2006. Wind erosion in tillage systems in the semiarid Pampa of Argentina. *Journal of Arid Environments* **69**: 29–39.

Casagrande G, Vergara G. 1996. Condiciones climáticas de la región. In *Labranzas en la Región Semiárida Argentina*, Buschiazzo DE, Panigatti J, Babinec F (eds). Instituto Nacional de Tecnología Agropecuaria: Santa Rosa, Argentina; 11–18.

Covas G, Glave A. 1996. *El deterioro del ambiente en la Argentina* (suelo, agua, vegetación). Fundación para la Ciencia, la Ecucación y la Cultura: Buenos Aires; 109–114.

Dregne HE. 1986. Desertification of arid lands. In *Physics of Desertification*, El-Baz F, Hassan MHA (eds). Martinus Nijhoff: Dordrecht.

Fryrear DW. 1986. A field sediment sampler. *Journal of Soil and Water Conservation* **41**: 117–120.

Fryrear DW, Saleh A, Bilbro JD, Schomberg HM, Stout JE, Zobeck TM. 1998. *Revised Wind Erosion Equation (RWEQ)*. Technical Bulletin 1, Southern Plains Area Cropping Systems Research Laboratory, Wind Erosion and Water Conservation Research Unit, USDA-ARS.

Hagen LJ. 1991. A wind erosion prediction system to meet users need. *Journal of Soil and Water Conservation* **46**: 106–111.

Michelena RO, Irurtia CB. 1995. Susceptibility of soil wind erosion in La Pampa Province, Argentina. *Arid Soil Reserearch and Rehabilitation* **9**: 227–234.

Saleh A. 1993. Soil roughness measurement: chain method. *Journal of Soil and Water Conservation* **48**: 527–529.

Skidmore EL. 1965. Assessing wind erosion forces: directions and relative magnitudes. *Soil Science Society American Proceedings* **29**: 587–590.

Skidmore EL. 1986. Wind erosion climatic erosivity. *Climatic Change* **9**: 195–208.

Stout JE, Zobeck TM. 1996. The Wolfforth field experiment: a wind erosion study. *Soil Science* **161**: 616–632.

Torres CG, Fernández GS. 2000. Erosión actual en los suelos agrícolas del valle de San Franciso, Jujuy. *Proceedings of the XVII Argentinean Congress of Soil Science, Mar del Plata, Argentina* (available on CD).

USDA. 1996. *WEPS (Wind Erosion Prediction System). Technical Documentation. Beta Release 95-08.* U.S. Department of Agriculture: Washington DC.

Van Pelt RS, Zobeck TM, Potter KN, Stout JE, Popham TW. 2004. Validation of the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) for single events. *Environmental Modelling and Software* **19**: 191–198.

Walkley A, Black IA. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**: 29–38.

Woodruff WP, Siddoway FH. 1965. A wind erosion equation. *Soil Science Society of America Proceedings* **29**: 602–608.

Zingg AW, Woodruff NP. 1951. Calibration of a portable wind tunnel for the simple determination of roughness and drag on field surfaces. *Agronomy Journal* **43**: 191–193.

Zobeck TM. 1991. Abrasion of crusted soils: influence of abrader flux and soil properties. *Soil Science Society of America Journal* **55**: 1091–1097.

Zobeck TM. 2002. Erosion by wind, Field Measurement of. In *Encyclopedia of Soil Science*. Marcel Dekker; 503–507.

Zobeck TM, van Pelt RS. 2006. Wind-induced dust generation and transport mechanics on a bare agricultural field. *Journal of Hazardous Materials* **132**: 26–38.

Zobeck TM, van Pelt RS, Stout JE, Popham TW. 2001. Validation of the revised wind erosion equation (RWEQ) for single events and discrete periods. *Proceedings of the International Symposium on Soil Erosion Research for the 21th Century*, 3–5 January, Honolulu; 471–474.

Zobeck TM, Sterk G, Funk R, Rajot JL, Stout JE, van Pelt SR. 2003. Measurement and data analysis methods for field-scale wind erosion studies and model validation. *Earth Surface Processes and Landforms* **28**: 1163–1188.

DOI: 10.1002/esp